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# FIXED-BASE-SIMULATOR EVALUATION OF A PILOT'S TERRAIN-FOLLOWING DISPLAY WITH VARIOUS MODES OF PRESENTING INFORMATION

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

An exploratory study was made of human ability to use a visual display to guide a high-speed aircraft in close proximity to the terrain. The control dynamics of a small aircraft flying near sea level at a Mach number of 1.2 were simulated on an analog computer interconnected with a two-axis side-arm controller and a cathode-ray tube display. The pilot's task was to guide the aircraft as closely as possible to simulated terrain while minimizing a heading error. No motion cues or other environmental stresses were provided.

It was noted that the pilot's performance was markedly influenced by variations in the visual display of the aircraft attitude and position relative to the terrain.

A 1-1/2-hour sustained terrain-following task with this fixed-base simulation revealed no major degradation in pilot performance.

INTRODUCTION

The high-speed, low-level flight is a particularly demanding mission of a tactical fighter during all-weather operation. This type of mission requires a method for controlling the flight path of the aircraft to maintain close proximity to the terrain when visual conditions are inadequate. Previous studies have considered methods varying from manual control by a pilot viewing a radar presentation to completely automatic terrain-following systems. The results of many of these investigations are summarized in reference 1.

A terrain-following system must provide sufficient information so that the pilot can either control the aircraft manually or monitor the performance of a completely automatic system to effect manual recovery in an emergency. Though a number of particular terrain-tracking displays have been tested, there appears to be a lack of information regarding human ability to use such displays for extended periods of time. Also, not much data is available regarding the effects of varying the information presented on these displays.

As a part of a general NASA study of the pilot-vehicle system for advanced aircraft missions, a fixed-base simulator was used to study manual terrain-following performance as affected by the type of information displayed. The vehicle simulated was an attack aircraft. The specific

objectives of this initial study were to evolve a situational display suitable for general research on the terrain-following task, noting the effects of the display on performance. The situational display was to provide the pilot continuously with readily interpretable information of the present position and attitude of the aircraft with respect to the terrain and with predictive information so that he can plan and execute a low ground-clearance flight path. It was assumed that the following information would be readily available as quantified data: (1) absolute height above the terrain directly below; and (2) angular measures from the horizon to the terrain at two fixed slant ranges.

It is emphasized that the simulation of the terrain-following task discussed in this report included no motion effects on the pilot, which at this speed and flight level could be very severe. It is also pointed out that the complexities of aircraft management, that is, power control, trim, navigation, etc., were reduced to a simplified control of the flight path. Further, this investigation was limited to a fixed course task where only the terrain in a straight line ahead of the aircraft was considered. The investigation included an evaluation of use of a terrain-following display for relatively long time periods and a comparison of the results obtained from the present investigation with those of previous studies.

#### SYMBOLS

A	aircraft altitude, ft
H	aircraft height above terrain, ft
$\bar{K}$	mean of variable K; for example, $\bar{A}$ is the mean aircraft altitude
N	number of data points in sample
r	correlation coefficient
$S_K$	standard deviation of variable K; for example, $S_A$ is the standard deviation of aircraft altitude
s	Laplace operator
T	terrain altitude, ft
$\alpha$	angle of attack
$\alpha_0$	trim angle of attack
$\delta_a$	aileron deflection
$\delta_e$	elevator deflection

$\theta$  pitch attitude  
 $\phi$  bank angle  
 $\psi$  yaw angle  
 $\omega_n$  aircraft undamped short-period natural frequency in pitch, radians/sec  
 $\zeta$  aircraft short-period damping ratio in pitch

## METHOD

### Equipment

The equipment used in providing a rudimentary simulation of the problem was an oscilloscope for presentation of steering information, a two-axis side-arm controller, a chair, an analog computer plus a low-frequency function generator, a Gaussian noise generator and a motorized switch for computation of the terrain kinematics and aircraft dynamic response and an eight-channel strip recorder for data recovery.

### Simulation

The aircraft dynamics simulated (appendix A) were representative of an attack aircraft flying near sea level at a Mach number of 1.2. Several simplifications in these dynamics were programmed on the analog computer:

1. Variations in thrust and velocity were omitted.
2. Only small perturbations about straight and level flight were considered.
3. Only pitch and roll transfer functions were simulated.
4. The heading angle as presented was included in the problem only to increase the pilot's workload, and though it was somewhat realistic, it was not a true representation of this aircraft type.

A Gaussian noise generator and analog equipment provided the altitude variation. Delay circuitry was employed to represent points 10 seconds ahead (2-1/2 miles), 5 seconds ahead (1-1/4 miles), and directly beneath the aircraft. As explained in appendix B, where the terrain generation is described in greater detail, two different "terrains" were used in this investigation. The first was somewhat rough as compared to a sample of California terrain, but was used throughout the display evolution phase. After a suitable display was established, less severe terrain was used for the concluding tracking run.

The situational display was presented on a 5-inch cathode-ray tube (CRT) and at all times contained elements depicting the horizon reference, heading, and the terrain at points 0, 5, and 10 seconds ahead of the aircraft. This display was similar to that used in a previous study, where nine test pilots did terrain-following in a G-seat with different wind gust levels simulated (ref. 2), in that it presented the same kind of information. However, in the current study, several changes in the method of presentation were made during the study and results noted. Figure 1 is a sketch of an aircraft in the terrain-following mode. Figure 2 presents the variations in the situational display, depicting the attitude and position of the aircraft (fig. 1) used in the study.

### Test Setup

The subject was seated so that his line of vision was perpendicular to the CRT face and his eyes were approximately 19 inches from it. The pencil controller was placed on a stand to his right at a sufficient height so that he could rest his forearm flat on top of the controller while holding the control stick knob with his thumb, index finger, and forefinger. Figure 3 shows the subject's position relative to the CRT and controller.

For each terrain-following run the following data were recorded continuously: heading error, rate of climb, normal acceleration, bank angle, elevator angle, altitude above terrain, terrain height below multiplexed with aircraft altitude, and terrain height 10 seconds ahead.

Figure 4 is a block diagram of the experimental configuration.

### Test Procedure

Since this study was exploratory, the general approach was one of trial and revision of the situation display. First, a display with elements relatively common to experience was established and the pilot practiced following the terrain as closely as he could without contacting the ground until he felt that he was no longer improving his performance (10 to 20 minutes practice was usually required); then trial runs of approximately 30 minutes were made and time histories recorded. At this point, the pilot's subjective views along with his record determined changes to the display, and then the cycle was repeated. No effort was made to adjust for the learning of the subject throughout the evolution of the displayed information; consequently, his earlier performance on the unimproved display probably was poorer than it would have been if that display had been represented at the end of the test series. However, it was believed that the pilot's opinion and obvious discrete jumps in performance would obviate, at least for this exploratory study, establishing a balanced experimental plan to offset the effects of learning, fatigue, etc.

After acceptable displays for the simulated task were established, several terrain-following runs were made. Pen records of these runs were analyzed to obtain performance data.

The subject was the experimenter:<sup>1</sup> male; 37 years old; moderate experience as controller of flight simulators; approximately 2000 flying hours in light aircraft, rated as commercial pilot, Single Engine Land (S.E.L.) flight instructor.

The following table summarizes the data that were analyzed.

Designation	Figure	Display	Task duration, min	Terrain simulation
		Description		
C	2(c)	Terrain ahead displayed as angular measures, $6^{\circ}$ /cm on CRT	15	High frequency terrain. Peaks to about 2500 feet.
D	2(d)	Terrain ahead displayed as relative height, 333 ft/cm, with altimeter	90	"
E	2(e)	Terrain displayed as relative height, 333 ft/cm, maximum of $T_{10}$ added	6	"
F	2(f)	Display same as E except pitch angle scaled $2.2^{\circ}$ /cm and heights scaled 250 ft/cm.	15	Low frequency terrain. Peaks to about 2500 feet.

## RESULTS AND DISCUSSION

### Effects of Display Mode on Terrain-Following Performance

Several display modes, conceptually similar but different in detail (figs. 2(a) through 2(e)), were evaluated. Appendix C describes in some detail the evolution of the various display modes evaluated and some qualitative impressions of the pilot with regard to the suitability of the displays for the terrain-following task.

In the present section, a summary of terrain-following performance for several selected display modes is provided in the following table. (A discussion of the statistics used to evaluate terrain-following performance is given in appendix D; however, a brief description is repeated here.) In the

<sup>1</sup>Terrain-following performance evaluation in a subsequent study indicated that the performance levels of two Ames test pilots and of the subject of the present study were roughly equivalent.

table,  $r$  is the correlation coefficient between the terrain altitude  $T$  and the aircraft altitude  $A$ ;  $S_A$  and  $S_T$  are the respective sample standard deviations;  $\bar{H}$  and  $S_H$  are the sample mean and sample standard deviation of the aircraft height above the terrain, that is,  $H = A - T$ ;  $N$  is the number of independent sample points used to determine the above statistics.

Display	Description	N	Sampling rate,* sec	r	$S_A/S_T$ , ft	$\bar{H}$ , ft	$S_H$ , ft
C	Terrain ahead displayed as angular measures, 6°/cm on CRT	80	10	0.71	$\frac{411}{304} = 1.35$	505	292
D	Terrain ahead displayed as relative height, 333 ft/cm, with altimeter	484	10	.90	$\frac{421}{276} = 1.52$	560	207
E	Terrain displayed as relative height, 333 ft/cm, maximum of $T_{10}$ added	36	10	.94	$\frac{500}{386} = 1.30$	384	193

\*The determination of sampling rate is explained in appendix B.

The improvement in performance as the display was evolved is quite evident in the data of this table. The correlation coefficient,  $r$ , a measure of the pilot's ability to place the flight path of the aircraft in phase with the terrain, shows a consistent increase to 0.94, the value obtained for display E. The ratio of  $S_A$  to  $S_T$  approaches 1 (from the "overcontrol" side) as the correlation coefficient approaches 1. Both the mean height above the terrain,  $\bar{H}$ , and the standard deviation of height,  $S_H$ , show consistently decreasing values as improvements were made to the display.

Figures 5, 6, and 7 are histograms of aircraft height above the terrain and graphically show this improvement in performance as the display was improved.

Terrain-following was also done with what was considered to be an improved version of display E, namely, display F; however, the terrain simulated was changed at this point in the study and, hence, the results were not directly comparable. This final display is described in appendix C.

#### Terrain-Following for an Extended Period of Time

The data obtained from the 90-minute terrain-following run using display D and an altimeter were analyzed by 10-minute periods and are presented below. Note that the first 10 minutes of this task were allowed for practice and were not analyzed.



10-minute time period	N	r	$S_A/S_T$ , ft	$\bar{H}$ , ft	$S_H$ , ft
1	61	0.93	$\frac{428}{268} = 1.60$	527	205
2	61	.81	$\frac{323}{189} = 1.71$	589	202
3	61	.90	$\frac{458}{311} = 1.47$	589	222
4	57*	.94	$\frac{526}{338} = 1.56$	601	241
5	61	.92	$\frac{373}{264} = 1.41$	526	166
6	61	.95	$\frac{333}{228} = 1.46$	508	134
7	61	.88	$\frac{438}{301} = 1.46$	613	222
8	61	.89	$\frac{419}{269} = 1.56$	530	217
Total	484	.90	$\frac{421}{276} = 1.52$	560	207

\*Four samples occurred during a reset to correct for computer drift and were removed.

It appeared that there was a period of adjustment and settling down at the beginning of this run (time periods 1 and 2) followed by a period of sustained performance showing a slight improvement toward the end (time periods 3 to 6) and ending with a slight reduction in performance (time periods 7 and 8). In the last two minutes of this run, there was a near miss of approximately 40 feet, followed by slightly erratic performance; however, this was due to the subject-operator's looking away from the display to view a watch. In spite of these noticeable differences in performance, it can be concluded that no significant changes in performance were evident over the 80-minute portion of this 1-1/2-hour tracking run.

As the task extended through time, the subject experienced several brief periods when the signals on the CRT appeared confused (i.e., blurred together and lacking meaning); however, his recovery was rapid enough not to affect his performance noticeably. This blurring may have been aggravated by the intensity or flickering of the CRT; however, it was not investigated further. It was evident during these simulated terrain-following tasks that the subject could be allowed very little time for diverting his eyes away from the display

scanning pattern without a subsequent effect on his performance. As mentioned above, the mere requirement of reading a wrist watch could have a marked effect on terrain-following performance.

A general feeling of tenseness was experienced throughout the run, followed by a mild feeling of fatigue after culmination of the task.

Though normal acceleration (at the center of gravity of the simulated vehicle) was recorded, it was doubtful that this measure had too much meaning in these tests; that is, had there been motion feedback, the over-all acceleration might have been reduced by the pilot's reluctance to impose sizable loads upon himself, or increased by coupling between the pilot, control system, and aircraft dynamics. It was noted that the maximum accelerations decreased from -2.3 and +6.0g for display C to -2.0 and +4.7g for display E, which corresponded more closely to results from actual terrain-following flights as reported in reference 3. A more detailed comparison with the data of this reference is made in the next section.

#### Comparison With Other Terrain-Following Data

In order to provide some information on the correspondence of the results of the present study with results of other terrain-following investigations, the following table was prepared. Selected portions of the flight data of reference 3 and the moving-cockpit data of reference 4 were extracted and analyzed. The results for display F (see appendix C) were used for comparison with previous data since the terrain characteristics used with this display corresponded closely to the actual terrain flown over in the flight study.

Task	Description of terrain-following task	N	Sampling rate*	r	$S_A/S_T$ , ft	$\bar{H}$ , ft	$S_H$ , ft
1	Visual in a Hunter 6 (single seat fighter) over hilly desert at Mach number 0.88 with minimum effort. Gust effects were marked to unpleasant. Maxima acceleration, 0 and +1.7g.	36	one per 10 sec	0.83	$\frac{362}{468} = 0.77$	608	261
2	Same as 1 above but at Mach number 0.7 with maximum effort. Gust effects were marked to unpleasant. Maxima of acceleration, -0.6 and +2.4g.	36	one per 10 sec	.966	$\frac{545}{506} = 1.08$	306	142
3	Instrumented in a G-seat simulator using a compensatory height tracking display and other instruments at Mach number 0.9. Short-period longitudinal dynamics were: $\omega_n = 6.3$ radians/sec, $\zeta = 0.4$ ; gusts at 6 ft/sec rms.	17	one per 10 sec	.987	$\frac{129}{121} = 1.07$	202	22
---	Current study using display F and low-frequency terrain. Velocity simulated: Mach number 1.2. Short-period longitudinal dynamics: $\omega_n = 6.6$ radians/sec, $\zeta = 0.3$ ; no gusts. Maxima of acceleration, -0.5 and +3.0g (neglecting sharp spikes).	30	one per 30 sec	.94	$\frac{384}{351} = 1.09$	296	131

\*The sampling rate for tasks 1-3 was arbitrary since the terrains were not analyzed for autocorrelation.

The data for tasks 1 and 2 were obtained from reference 3. The improvement in performance from task 1 to task 2 is very apparent in this table. That the pilot of task 1 was smoothing or filtering the terrain is suggested by the lower value of  $r$  coupled with the ratio of  $S_A/S_T$  being less than 1. The data for task 2 give considerable support to the description "maximum effort." The value of  $r$  approaches 1, the ratio of  $S_A/S_T$  approaches 1, and  $\bar{H}$  is low relative to the type of terrain.

When the data of task 2 were compared with that of the current study for display F, similarities were noted in the values of  $S_A/S_T$ ,  $r$ , and  $\bar{H}$ , though slightly better terrain-following was evident in the performance of task 2. That the value of  $S_H$  for task 2 was slightly higher was attributed to the higher amplitude of the terrain for that task (as explained in appendix D, the values  $S_H$  and  $S_T$  are related). A histogram of height above the terrain performance for display F is presented in figure 8. A similar figure for task 2 is presented in figure 9. It was noted also that the acceleration limits encountered in task 2, -0.6 to +2.4g, were somewhat similar to those simulated for performance with display F, -0.5 to +3.0g.

Task 3 in the above table, sampled from reference 4 (fig. B-1), approaches perfect terrain-following at a fixed clearance height. That this performance level was possible, considering that the pilot did not have information of the terrain ahead (control was achieved primarily by use of an altitude error display and a subsidiary instantaneous rate-of-climb instrument), is attributed primarily to the subdued terrain represented ( $S_T = 121$  ft). This example is mentioned to emphasize that pilot-vehicle terrain-following performance can legitimately be compared only when the "terrains" involved are relatively similar in configuration.

In conclusion, if the considerable differences in environment are neglected, the similarity of the "terrains" (see figs. 10(a) and 10(b) and the discussion in appendix B) and performance of task 2 and the current study suggest that display F provided much of the information obtained from a straight-ahead view through the windshield of a low-flying aircraft.

#### CONCLUDING REMARKS

From results of a fixed-base simulation of a low-level, high-speed terrain-following task, the following observations were made:

Comparative terrain-following performance measures for several display modes showed that performance improved progressively as:

1. The terrain points ahead were displayed as heights relative to the aircraft, rather than as angles relative to the horizon,

2. The pitch angle was magnified, compared to the scaling for standard attitude instruments for aircraft,

3. An indicator was added, providing continuous information on maximum heights of the terrain ahead (i.e., maxima of terrain 10 sec ahead).

The results of sustained simulated terrain following with a visual display for 1-1/2 hours indicated that no significant degradation in performance had occurred, though the subject was mildly fatigued.

The close correspondence between the terrain-following results of the present study and those of a previous flight study (for roughly similar terrains) suggests that the display used provided much of the information provided by a straight-ahead view through the windshield of a low-flying airplane.

Ames Research Center  
National Aeronautics and Space Administration  
Moffett Field, Calif., June 15, 1964

## APPENDIX A

### SIMULATION

#### Aircraft Dynamics

The following transfer functions were programmed on an analog computer to simulate the dynamics of an aircraft flying near sea level at a Mach number of 1.2.

##### Longitudinal:

$$\begin{aligned}\frac{\theta}{\delta_e} &= \frac{-50.3(S + 1.07)}{S(S^2 + 3.61 S + 44.2)} , & \text{radian/radian} \\ \frac{\ddot{A}}{\delta_e} &= \frac{-23,844(S - 2.9)}{S(S^2 + 3.61 S + 44.2)} , & \frac{\text{ft/sec}^2}{\text{radian}} \\ \frac{A}{\delta_e} &= \frac{1}{S^2} \frac{\ddot{A}}{\delta_e} , & \frac{\text{ft}}{\text{radian}}\end{aligned}$$

##### Lateral directional: (sideslip assumed zero)

$$\begin{aligned}\frac{\varphi}{\delta_a} &= \frac{-118}{S(S + 3.79)} , & \frac{\text{radian}}{\text{radian}} \\ \frac{\dot{\psi}}{\delta_a} &= \frac{K}{S} \frac{\varphi}{\delta_a} , & \frac{\text{radian}}{\text{radian}}\end{aligned}$$

K was arbitrarily adjusted to give a  $\dot{\psi}$  of 1/40 cm/sec per degree of  $\varphi$  on the CRT.

#### Control Characteristics

The side-arm pencil controller forces were:

##### Elevator:

0.067 lb/deg of elevator maximum travel, 0.8 in. at 1 lb

##### Aileron:

0.16 lb/deg of aileron maximum travel, 1.3 in. at 1.6 lb

## APPENDIX B

### DESCRIPTION OF TERRAIN GENERATED

An examination of cross-sectional cuts through terrain suggested that a reasonable approximation of a section of terrain could be accomplished by summing a long- and a short-period wave, where the long-period wave was sinusoidal to represent gradual changes in terrain elevation and the short-period wave was peaked to represent hilltops and valleys. For the purpose of this study the long-period terrain waves were ignored since they appeared to have a relatively gradual rate of ascent and descent and would probably introduce only minor problems in terrain-following. The short-period waves, however, would obviously introduce considerable difficulty in low-level terrain-following, and, hence, were used here to simulate this portion of terrain characteristics.

It was empirically determined that a reasonably good approximation to the terrain short-period waves could be obtained by squaring filtered Gaussian noise. The filter used for the bulk of this study was second order with a damping ratio of 0.7 and a natural frequency of 0.2 radian/second (0.13 cycles/mile). The amplitude was adjusted so as to generate peaks of about 1000 feet, with occasional tops above 2000 feet. This produced "terrain" which, as viewed from the aircraft at a Mach number of 1.2, sometimes varied up to 300 ft/sec. Figure 11(a) presents a typical histogram of terrain rates. Figure 11(b) is a sample of the terrain cross section as generated.

A somewhat similar scheme for terrain generation was employed with a reasonable match to real terrain by the Cornell Aeronautical Laboratory in reference 5. In this more complicated scheme the filtering and squaring was done digitally with random numbers and included a long-period effect. The appearance of the terrain generated for that study, however, was not markedly different from the appearance of the terrain resulting from the rather simple scheme used in this report.

Prior to the last tracking run of this study the terrain as generated was compared with a cross section of hilly California terrain, Oakland to Avenal via V 107, and it was decided that though the amplitude of the generated terrain reasonably approximated the amplitude of the high-frequency content of the California terrain, the occurrence of "hills" in the generated terrain was too frequent. Subsequently, the natural frequency of the filter was reduced to 0.067 radian/second (0.043 cycle/mile) as a better approximation. Figure 12 shows a sample of each of these "terrains."

In the course of this investigation the terrain-following performance with display F (terrain filter set at  $\omega_n = 0.067$  radian/second) was compared to a sample of terrain-following performance extracted from reference 3, in which the terrain was actual hilly African desert. In comparing these two "terrains" it was noted that the African desert had a more plateau-like character with each hill rising to approximately 1500 feet, while the height of the hills of the current study exhibited more variability but a lower

average. Also, the occurrence of hills in the sample of African desert was more frequent than in the current study; however, when the two terrains were portrayed on the same time scale as they would appear when viewed from the aircraft, this difference was not so apparent (figs. 10(a) and 10(b)).

It was believed that the major difference between these two terrains as viewed from the aircraft would be that the African desert was rougher and required more control but also contained fewer surprises (e.g., the sudden appearance of a hill over 2000 feet preceded by a series of hills under 700 feet).

The terrain as generated was designated as the terrain height 10 seconds ahead, and then, by use of 5- and 10-second Pade delay circuits, the terrain heights at points 5 seconds ahead and directly below, respectively, were obtained. Notice that this technique of simulating the terrain always provided the height of the terrain ahead, even though in reality the pilot might not always have this information. For example, if the aircraft were quite close to the terrain and approaching a rather peaked hill, at some position of the aircraft, the terrain at fixed distances ahead might be on the far side of the hill and not be visible. It is reasoned that this ability to "look through" the hills in the simulation did not materially influence performance because it would occur only infrequently and would be noticeable only in the 10-second terrain-height indicator during or slightly before pushover; at this time, the pilot would not be attending to this indicator other than to note that it was not rising.

There was some curiosity concerning the distribution function of terrain amplitude as generated, since this was expected to appear to some extent in the distribution of height above the terrain. The output of the Gaussian noise generator used had the following amplitude distribution function:

$$f_X(x) = \frac{1}{\sqrt{2\pi} \sigma} e^{-\frac{x^2}{2\sigma^2}}, \quad -\infty < x < \infty$$

where  $\sigma$  was some arbitrary constant representing the standard deviation (also RMS in this case since the mean was zero).

The effect of filtering (a linear operation) would only change  $\sigma$ , leaving the form of the distribution function unchanged.

The effect of squaring the filter output, however, was to transform the distribution function to a function of  $T$ , where  $T = X^2$ :

$$\begin{aligned} f_T(t) &= f_X(X(t)) \left| \frac{dx}{dt} \right|^+, \quad X(t) = +\sqrt{t}, -\sqrt{t} \\ &= \frac{t^{-1/2} e^{-t/2\sigma^2}}{\sqrt{2\pi} \sigma}, \quad 0 < t < \infty \end{aligned}$$

Let

$$Z = \frac{T}{\sigma^2} , \text{ a normalized variate}$$

Then

$$f_Z(z) = \frac{z^{-1/2} e^{-z/2}}{\sqrt{2\pi}} = \frac{z^{[(1/2) - 1]} e^{-z/2}}{[(1/2) - 1]! 2^{1/2}} , \quad 0 < z < \infty$$

which is a chi-square distribution with  $K = 1$  degree of freedom.

This was verified by fitting a chi-square distribution to a normalized sample of generated terrain and subjecting the fitted distribution to a goodness-of-fit test. The results indicated good agreement.

The implication of the foregoing discussion was that if the pilot of the current study did any smoothing of the terrain or if his height above the terrain was proportional to the terrain height, then the distribution function of height above the terrain would contain a chi-square element (when normalized by appropriate scaling) and would be skewed. This hypothesis is substantiated by histograms of height above terrain in figures 5 to 8.

Another consideration given to the terrain generated was the autocovariance introduced by the linear filter, inasmuch as it was expected that independent samples of data at discrete points in time would be desired for analysis. As suggested in reference 6, p. 20 ff, for a linear filter the solution of the approximation,  $\Delta\omega \Delta\tau = 1$  (where  $\Delta\omega$  is the spectral bandwidth and  $\Delta\tau$  is the correlation time), defines an interval outside of which the autocorrelation function takes comparatively small values (approximately 1/2 or less of the autocorrelation at  $\tau = 0$ ). For the terrain used in the bulk of this investigation  $\Delta\tau \approx 5$  seconds; for the terrain used in the concluding run  $\Delta\tau \approx 15$  seconds. This implied that sampling rates of about 10 and 30 seconds, respectively, might be used to obtain reasonably independent samples. This was verified by subjecting samples of the high frequency and the low frequency terrain to an investigation of the autocorrelation present. In the high frequency case (i.e.,  $\omega_h = 0.2$  radian/sec), the autocorrelation was negligible at  $\Delta\tau = 10$  seconds. In the low frequency case (i.e.,  $\omega_h = 0.067$ ), the autocorrelation was 70 percent at  $\Delta\tau = 10$  seconds, 30 percent at  $\Delta\tau = 20$  seconds, and 6 percent at  $\Delta\tau = 30$  seconds relative to the autocorrelation at  $\Delta\tau = 0$ .



## APPENDIX C

### EVOLUTION OF SUITABLE TERRAIN-FOLLOWING DISPLAY

Figure 1 is a sketch of an aircraft flying in proximity to the terrain. It is the attitude and relative position of the aircraft in this sketch that is shown in each of the subsequent sketches of the various situational displays used. The displays were evolutionary; that is, each successive display was identical to its predecessor except for the modifications discussed below.

#### Display A

The elements of the first display (fig. 2(a)) were established as follows. Because the primary reference in aircraft control is the horizon, a horizon bar was deemed a requirement of the display. The zero reference and scaling used were similar to those of a standard aircraft gyro horizon instrument. Also, because the distance to the terrain below is important in this task, this information was represented by a horizontal line displaced downward from the center of the display to indicate height directly above the terrain. The scaling set at 333 ft/cm permitted 1500-foot variations in height. In addition, it was assumed that predictive information required for successful terrain-following could be provided by using a vertical scanning pencil radar to determine inclination from the horizontal to points on the terrain at fixed ranges ahead. It was arbitrarily decided to use two such points spaced ahead at ranges equivalent to a 5- and a 10-second elapsed flight time. These time periods were not varied throughout this investigation. The scaling on these inclination angles was the same as the pitch angle, namely,  $15^\circ = 1 \text{ cm}$ , and the zero reference used was the CRT center.

Terrain-following attempts with this display were "catastrophic." The display lacked coherence between the terrain depicted and the horizon depicted; the pilot was required to read two different types of presentation superimposed upon each other in an unfamiliar fashion.

The horizon bar as displayed had the usual "inside out" orientation and its motion was comparable to the apparent motion of the horizon as viewed through the windshield. The terrain heights displayed had only a partial "inside out" orientation; that is, as the aircraft climbed up from the terrain, the terrain height indicators moved in the downward direction similar to the apparent downward motion of terrain perceived through the windshield of a climbing aircraft. However, as the aircraft was varied in pitch attitude only, no motion was evident on the terrain height indicators which conflicted with a complete "inside out" presentation of the terrain. It was this discrepancy which caused the display to give the impression of being two superimposed instruments, requiring divided attention, rather than the desired single instrument giving a unified "view" of the outside world.

### Display B

The second display attempt (fig. 2(b)) differed from the first only in the zero reference of the terrain ahead and below. In display B the center of the horizon bar was used as the zero point to give a complete "inside out" presentation. Thus, if a hilltop at the same elevation as the aircraft were ahead and the aircraft were held in level flight, each terrain indicator would rise to the center of the horizon bar and then fall in succession as the simulated aircraft passed over the hilltop.

Tracking efforts with this display were also unsuccessful, though a definite improvement was noted. The display, with the exception of the terrain-below indicator, gave a scaled down picture of the "real world" directly ahead as it would appear through the windshield. The scaling of displayed angles to real angles as would be seen through the windshield was 1 to 13 as determined from the subject's ocular distance from the display (19 in.) and the display scaling.

### Display C

To increase the magnification of angles to distant (10 sec) hills the scaling was increased so that terrain and pitch angles were  $6^\circ/\text{cm}$  on the CRT, figure 2(c). Though the subject's performance improved somewhat, it was still inadequate as shown by figure 13 which is a pen record of performance with this display. Small angles perceived in the 10-second-ahead indicator loomed up too quickly in the 5-second-ahead indicator for adequate terrain-following and collisions with hilltops were frequent. Apparently the predictive information available was being attenuated to the extent that the subject was unable to respond soon enough to the requirement for a hard pull-up.

### Display D

To give more magnification to the terrain ahead and to place the terrain-ahead elements and the height-below element together in a compatible dimension, the perspective effect was removed and the angles to the terrain ahead were transformed to approximate differences in altitude between the aircraft and the points ahead (fig. 2(d)). The scaling on the terrain ahead indicators was set at 333 ft/cm to agree with the scaling of the terrain directly beneath indicator. The resulting display gave an "inside out" orthographic portrayal of the outside world.

Apparently this display provided a strong prediction or lead cue, for the subject no longer flew into (or very near to) the fronts of the hills; instead, he tended to overcompensate and often acquired too much altitude before each hill. In general, his performance over the hilltops was erratic.

The subject's impression was that even though the display gave sufficient warning of the magnitude of approaching hills, there remained an indefiniteness as to the altitude differential between the aircraft and the peak ahead. This was most evident when the approaching peak was between the points where terrain heights were computed and at the same time the aircraft altitude was changing.

To allow the subject to fix the altitude of the peaks, a relative (to sea level) altimeter was added along side of the display. Thus, when the pilot saw a peak ahead of the aircraft in the 10-second-ahead display element, he estimated its height above the aircraft directly from the display and mentally added it to the altimeter reading to determine the relative altitude of that peak. Then the subject "climbed" above that altitude and felt secure that he would not contact the ground.

With this relatively crude technique of using display D and an altimeter, a 90-minute terrain-following run was made with no ground contacts.

#### Display E

In display E (fig. 2(e)) the need for the altimeter was eliminated because an additional element was introduced which represented the maximum altitude of the terrain 10 seconds ahead less the current altitude of the aircraft. This element, a single dot on the CRT y-axis, was allowed to coincide with the terrain 10-second-ahead bar as long as the terrain ahead was level or sloping upward. Should the indicator for the 10-second-ahead terrain begin to fall, indicating that a peak was approaching, the "memory" dot was left as an indication of the height of this peak relative to the altitude of the aircraft. At this time the pilot had 10 seconds to bring this dot to some distance below the horizon line so as to clear the peak ahead by a desired height. A button switch was also provided, which when activated by the subject, drove the "memory" dot back down to coincide with the 10-second-ahead terrain bar. A sample of terrain-following with this display is presented in figure 14.

#### Display F

Though display E appeared to provide all the required elements for reasonable tracking of the generated terrain, it was believed that a greater resolution of both pitch angle and terrain height would allow terrain-following with less ground clearance. Subsequently, the scaling on all height information was changed to 250 ft/cm (from 333 ft/cm) and the scaling on the pitch angle was changed to 2.2°/cm (from 6°/cm). This fairly high magnification for pitch angle was selected for several reasons. First, it appeared that level-flight-altitude control improved as the magnification of the pitch angle was increased. Within certain limits (not explored in this study) this effect was understandable, inasmuch as a fairly high resolution

of pitch angle became a prerequisite for good altitude control at the simulated velocity, especially since rate of climb information was not available to the pilot. Second, a limit on magnification of pitch angle was approximately established by terrain slope (i.e., some of the terrain slopes generated were as high as 300 ft/sec) or an inclination of  $13^\circ$ . Since the foregoing considerations placed the scaling of pitch angle at approximately  $2^\circ/\text{cm}$ , it was decided to take advantage of the fact that, for the 5-second-ahead terrain indicator, height and angle coincided if pitch scaling was  $2.2^\circ/\text{cm}$ ; that is, a point  $1\text{-}1/4$  miles ahead of the aircraft and 250 feet below the altitude of the aircraft would also be  $2.2^\circ$  below the horizon. This allowed a simultaneous presentation of the relative angle and the relative height to the terrain 5 seconds ahead. Thus, if the relatively small deviations in angle of attack that would occur at this flight mode were ignored, the pilot need only point the nose of the aircraft (indicated by the miniature airplane fixed in the CRT center) to a desired height above a point on the terrain 5-seconds-ahead indicator to know that, if he held this attitude, he would arrive over that point, in 5 seconds, at the preselected height. The scaling effect of display F is illustrated in figure 2(f).

Terrain-following performance with display F was not directly comparable with performance for any of the preceding displays since at this time the terrain generator was modified to better represent actual terrain (California hills, see appendix B). Because the terrain-following task was made easier by the terrain modification, the subsequent improvement in performance cannot be solely attributed to changes made to the display. A sample of terrain-following under these conditions is presented in figure 15.

## APPENDIX D

### METHOD USED TO EVALUATE TERRAIN-FOLLOWING PERFORMANCE

In order to assess the effects of changes in the visual display, of fatigue, etc., a relationship between the task and performance was defined so that, when sample data were analyzed, improvement or degradation of performance could be detected. Since the requirement was not to describe performance but only to rate performance, it was believed that the simple linear relationship of equation (1) would be adequate.

$$A(t) = aT(t) + b + e(t) \quad (1)$$

where

$A(t)$  aircraft altitude at time  $t$

$a$  slope parameter

$T(t)$  terrain altitude at time  $t$

$b$  translation parameter

$e(t)$  error in linear fit at time  $t$

It was assumed that performance was best when the aircraft was following the terrain contour exactly at a constant height. Though this may appear unrealistic, and possibly undesirable where high-frequency terrain is encountered, it was believed that performance improved when it tended toward this ultimate and vice versa.

To evaluate the parameters in equation (1), it was decided to use data at independent sample points; consequently, equation (1) becomes

$$A_i = aT_i + b + e_i \quad (2)$$

where the subscript denotes the  $i$ th sample.

To obtain independent samples, it was reasoned that the time interval for sampling need only be as great as that at which no autocorrelation was evident in the terrain since it was unlikely that the aircraft flight path would exhibit any autocorrelation beyond this interval. The method of determining this time interval was explained in appendix B.

The method of least squares was used to find values of  $a$  and  $b$  for which  $\sum_{i=1}^N e_i^2$  is a minimum; these are:

$$a = \frac{N\sum AT - \sum A \sum T}{N\sum T - (\sum T)^2} \quad (3)$$

$$b = \frac{\sum A - a\sum T}{N} \quad (4)$$

where the sums are over-all sample points.

Formulas (3) and (4) can be rewritten in the more familiar statistical notation (keeping in mind that no distribution functions have been assumed):

$$a = r \frac{S_A}{S_T} \quad (5)$$

$$b = \bar{A} - \bar{T} \left( r \frac{S_A}{S_T} \right) \quad (6)$$

where  $\bar{A}$  and  $\bar{T}$  are sample means,  $S_A$  and  $S_T$  are sample standard deviations, and  $r$  is the sample correlation coefficient. The elements of formula (5) were used as follows in evaluating terrain-following performance. The correlation coefficient,  $r$ , in the ultimate case would be 1.00 and any lower value, that is,  $1 > r > 0$ , would indicate a lack of phasing with the terrain or motion not associated with the terrain. The ratio,  $S_A/S_T$ , can be interpreted as representing the over-all amplitude ratio of aircraft motion to terrain motion and in the ultimate case would also be 1.00. A value greater than 1.00 would suggest that the pilot was either overcontrolling (i.e., flying high over the hilltops and low in the valleys) or was generally deviating about the desired flight path (the latter case would be excluded if the correlation coefficient were 1.00). If this ratio were less than 1.00, the inference could be made that the pilot was smoothing, or not responding to the terrain. For the purpose of this study, performance was considered to have improved when the values of  $r$  and  $S_A/S_T$  moved closer to 1.00, and to have degraded when  $r$  moved toward zero and  $S_A/S_T$  deviated from 1.00 in either direction.

Though the parameter  $b$  as determined in formula (6) is most useful in describing the flight path of the aircraft with respect to the terrain (i.e., eq. (1) fits the flight path to given terrain), it was decided to use the more familiar  $\bar{H}$ , mean height above the terrain, in assessing performance. Note that the substitution of  $\bar{A} = \bar{H} + \bar{T}$  in formula (6) gives:

$$b = \bar{H} + \bar{T} \left( 1 - r \frac{S_A}{S_T} \right) \rightarrow \bar{H} , \quad \text{as } r \frac{S_A}{S_T} \rightarrow 1 \quad \left. \vphantom{b = \bar{H} + \bar{T} \left( 1 - r \frac{S_A}{S_T} \right)} \right\} \quad (7)$$

$$\rightarrow \bar{A} , \quad \text{as } r \frac{S_A}{S_T} \rightarrow 0$$

which is another way of saying that  $\bar{H}$  is meaningful only if the aircraft flight path is approximating the terrain.

The standard deviation of aircraft height above the terrain,  $S_H$ , was also included in the tables of this report since it was anticipated that many readers would want this information; however, in doing so, it is pointed out that  $S_H$  is not independent of the other statistics already discussed.

$$S_H^2 = S_A^2 + S_T^2 - 2rS_AS_T \quad (8)$$

The appropriateness of assuming a linear relationship between aircraft flight path and terrain can be determined as follows. Equation (2) and formulas (5) and (6) give the following expressions for the mean and standard deviation of the error term in equation (2).

$$\bar{e} = \frac{1}{N} \sum_{i=1}^N e_i = \frac{1}{N} \sum_{i=1}^N \left[ A_i - r \frac{S_A}{S_T} T_i - \bar{A} + \bar{T} \left( r \frac{S_A}{S_T} \right) \right] = 0 \quad (9)$$

$$\begin{aligned} s_e &= \sqrt{\frac{1}{N} \sum_{i=1}^N e_i^2} = \sqrt{\frac{1}{N} \sum_{i=1}^N \left[ (A_i - \bar{A}) - r \frac{S_A}{S_T} (T_i - \bar{T}) \right]^2} \\ &= S_A \sqrt{1 - r^2} \end{aligned} \quad (10)$$

Formula (9) assures that the mean error in the fitted linear expression will always be zero. Formula (10), the standard deviation (or RMS since  $\bar{e} = 0$ ) of this error term, shows the dependence of the validity of a linear assumption on the value of the correlation coefficient.

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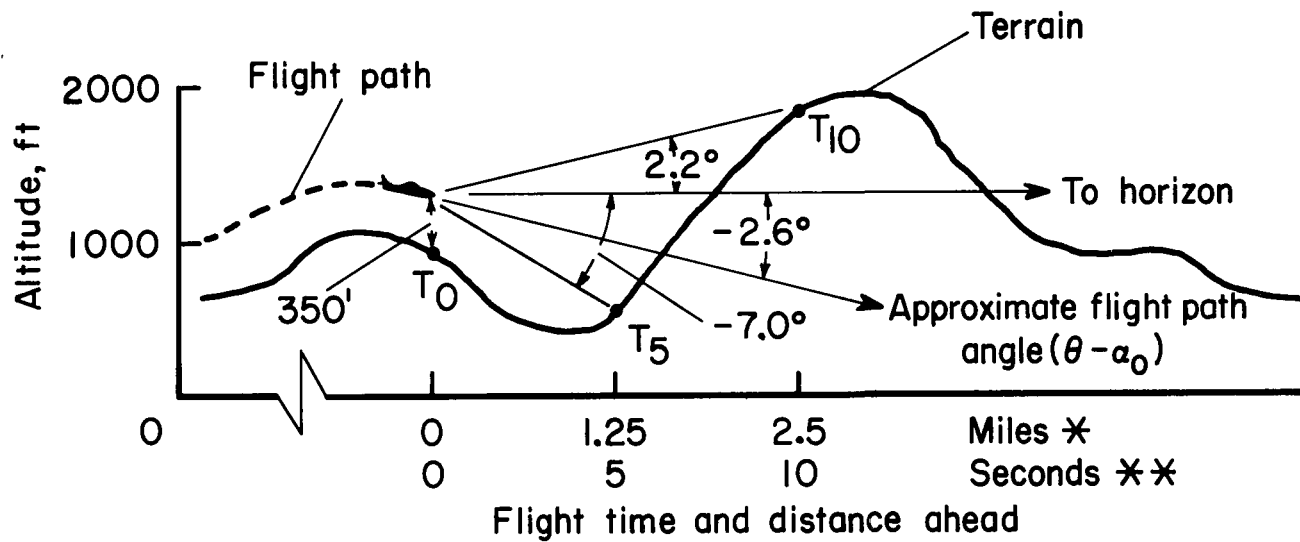
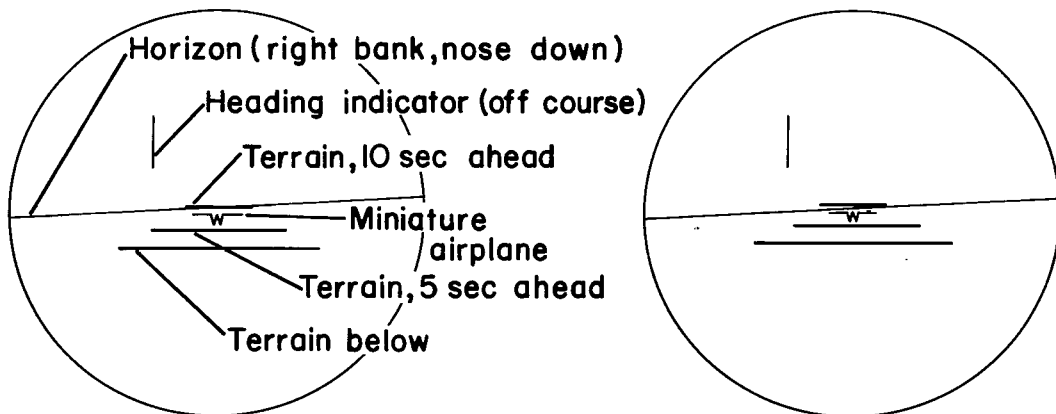
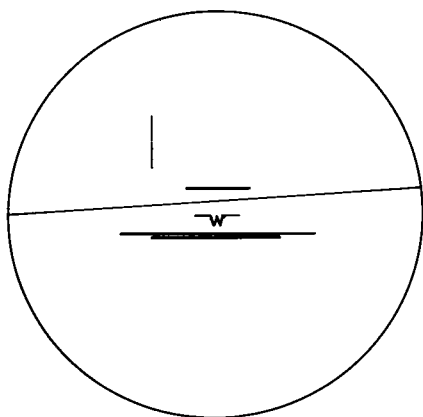


Figure 1.- Profile of flight path and terrain during terrain-following. (Attitude and position of aircraft depicted by each display in figure 2.)

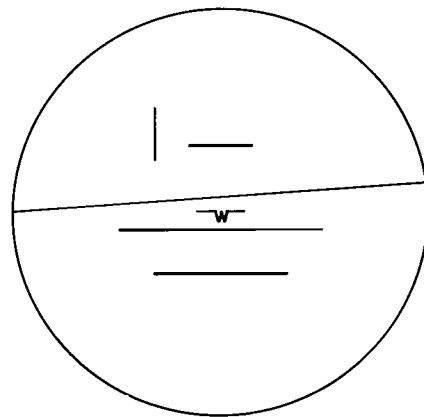


(a) Display A; angles to terrain ahead scaled  $15^\circ/\text{cm}$ , terrain below 333 ft/cm; scope center is zero reference.

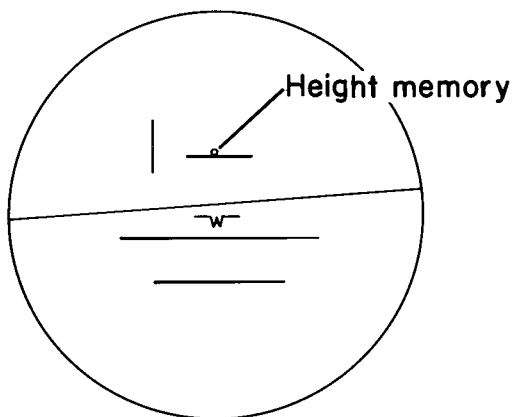
(b) Display B; same as A except zero reference of terrain translated to horizon center.



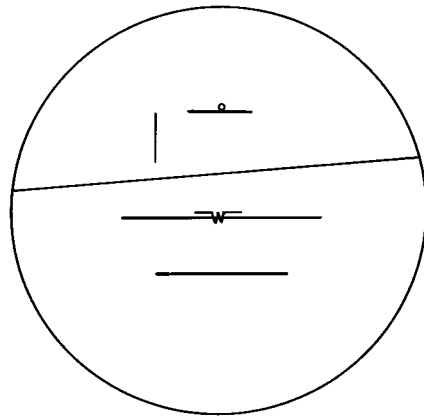
(c) Display C; pitch and terrain angles rescaled to  $6^\circ/\text{cm}$ .



(d) Display D; terrain ahead shown as relative heights; 333 ft/cm.



(e) Display E; height memory dot (maxima of terrain 10 sec ahead) added.



(f) Display F; heights rescaled to 250 ft/cm; pitch angle =  $2.2^\circ/\text{cm}$ .

Figure 2.- Variations in situational displays.

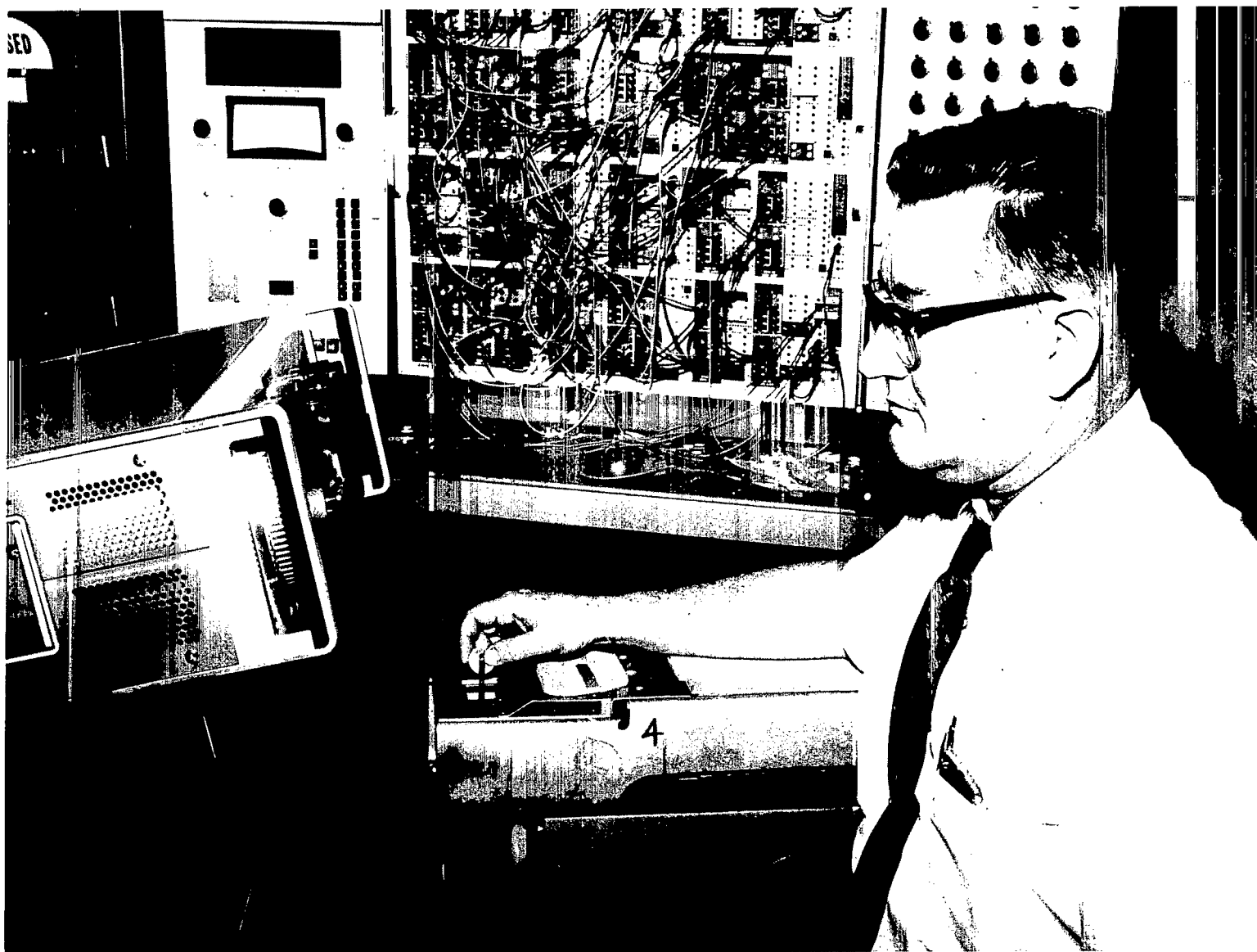


Figure 3.- Subject's position relative to the CRT and controller.

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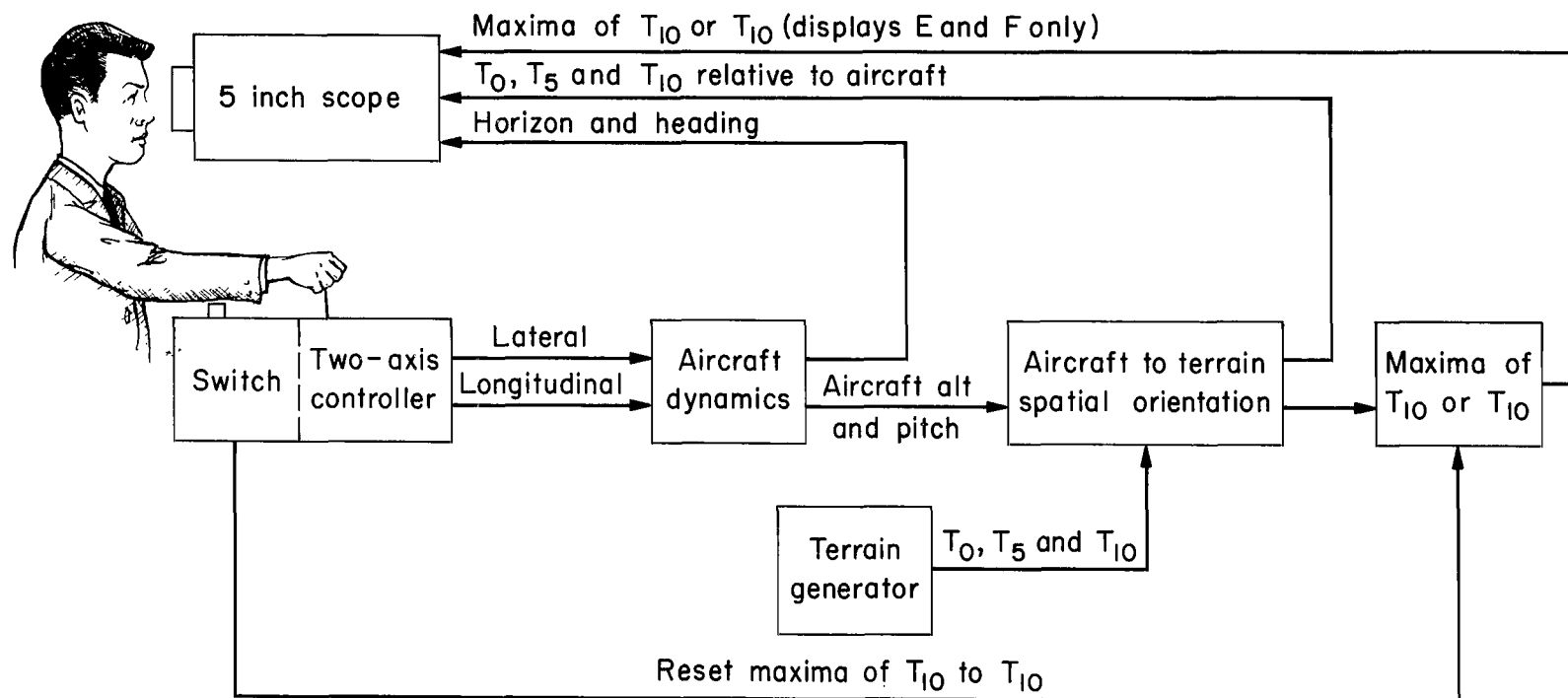


Figure 4.- Block diagram of experimental configuration.

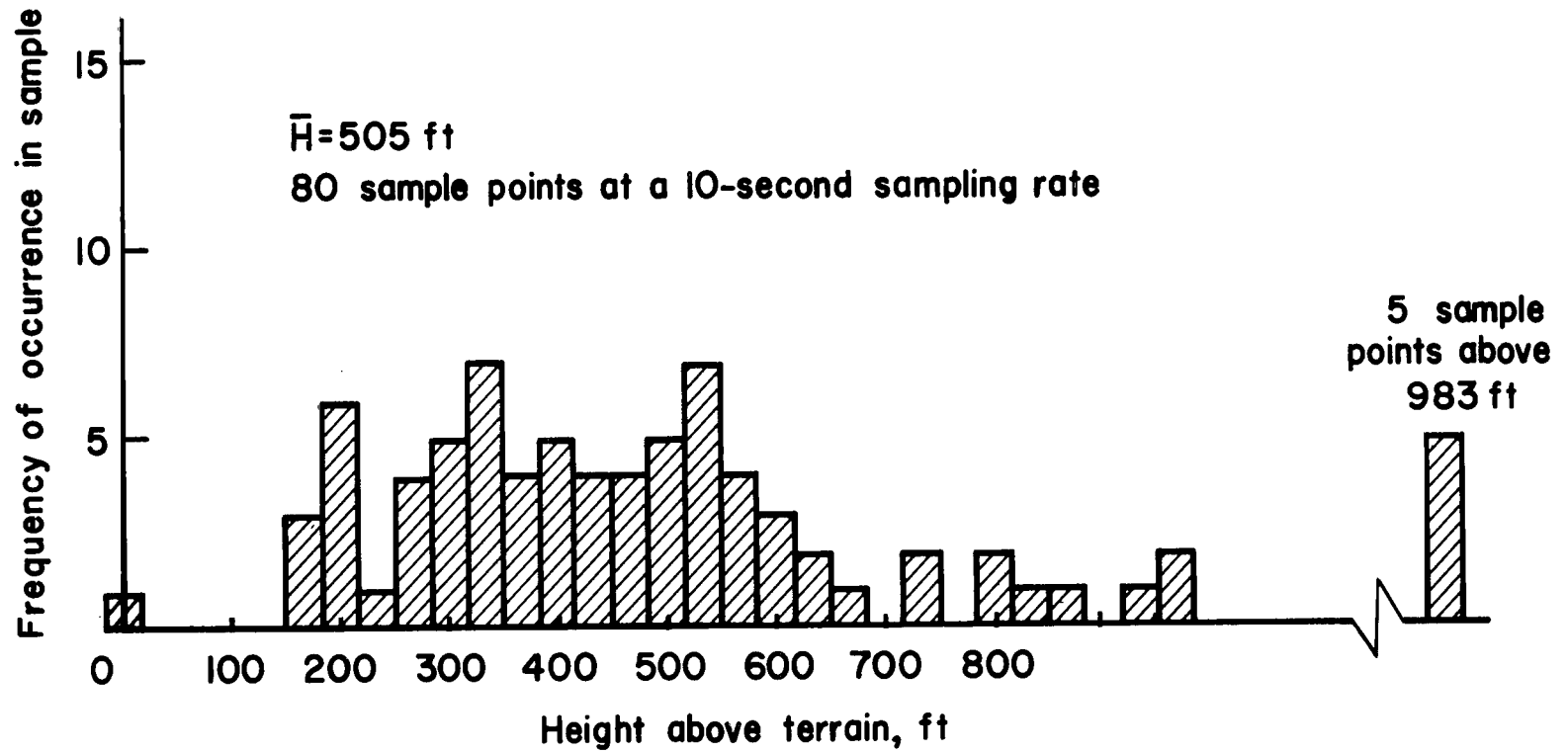


Figure 5.- Histogram of height above terrain; simulated terrain-following using display C.

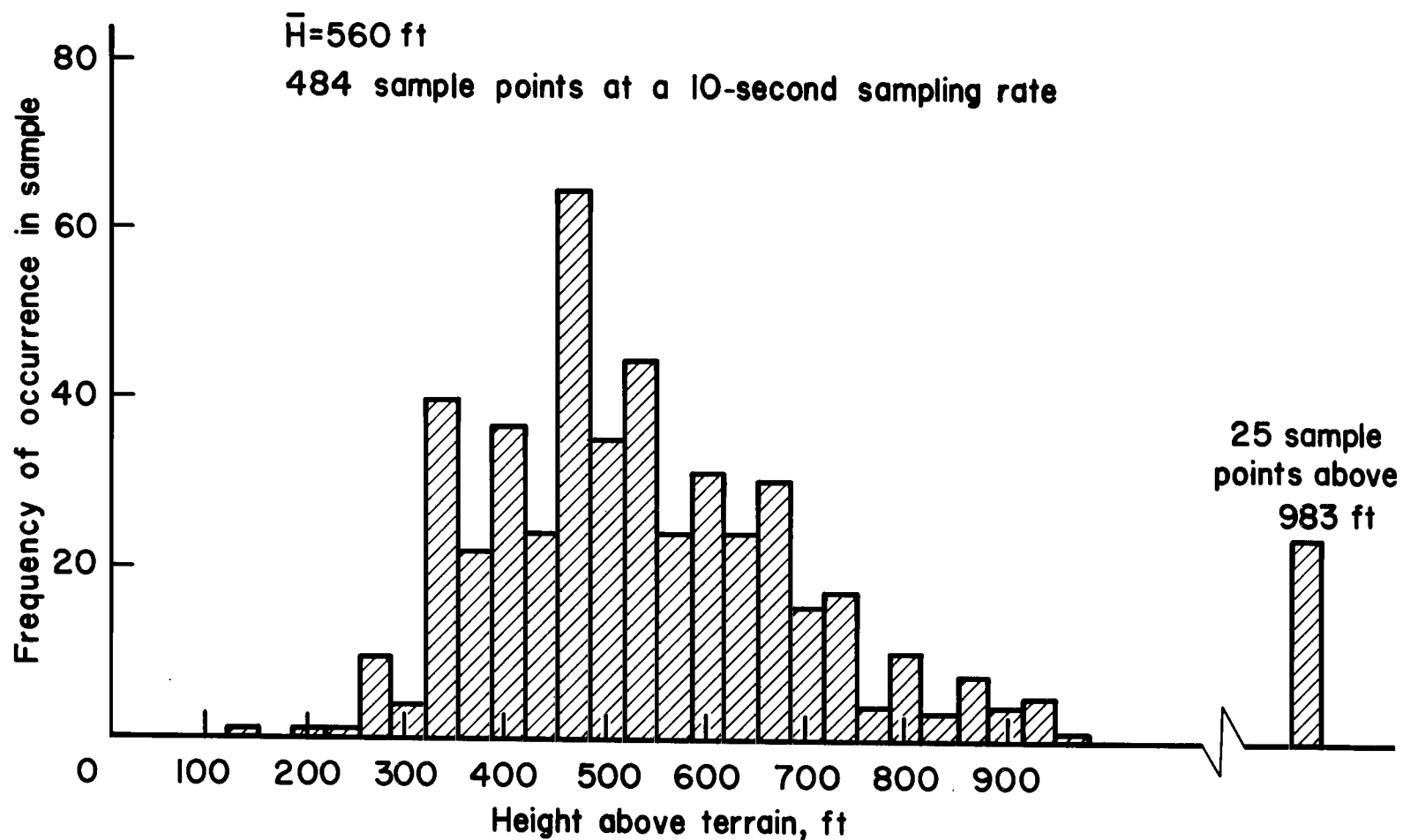


Figure 6.- Histogram of height above terrain; simulated terrain-following using display D and an altimeter.

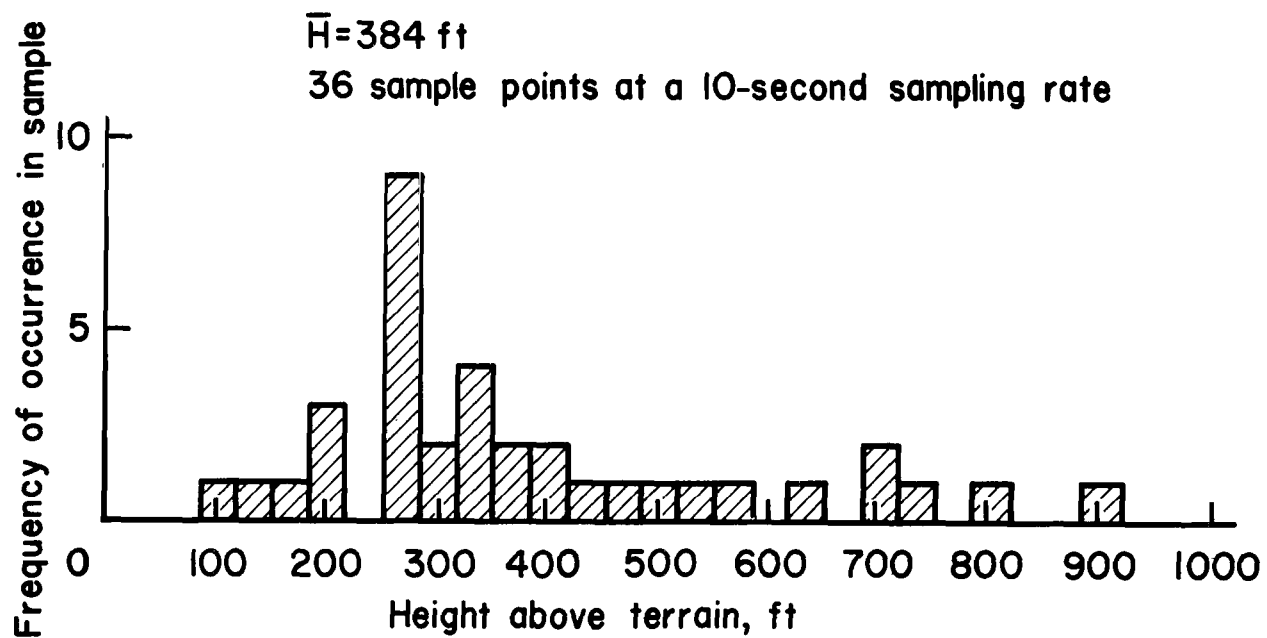


Figure 7.- Histogram of height above terrain; simulated terrain-following using display E.

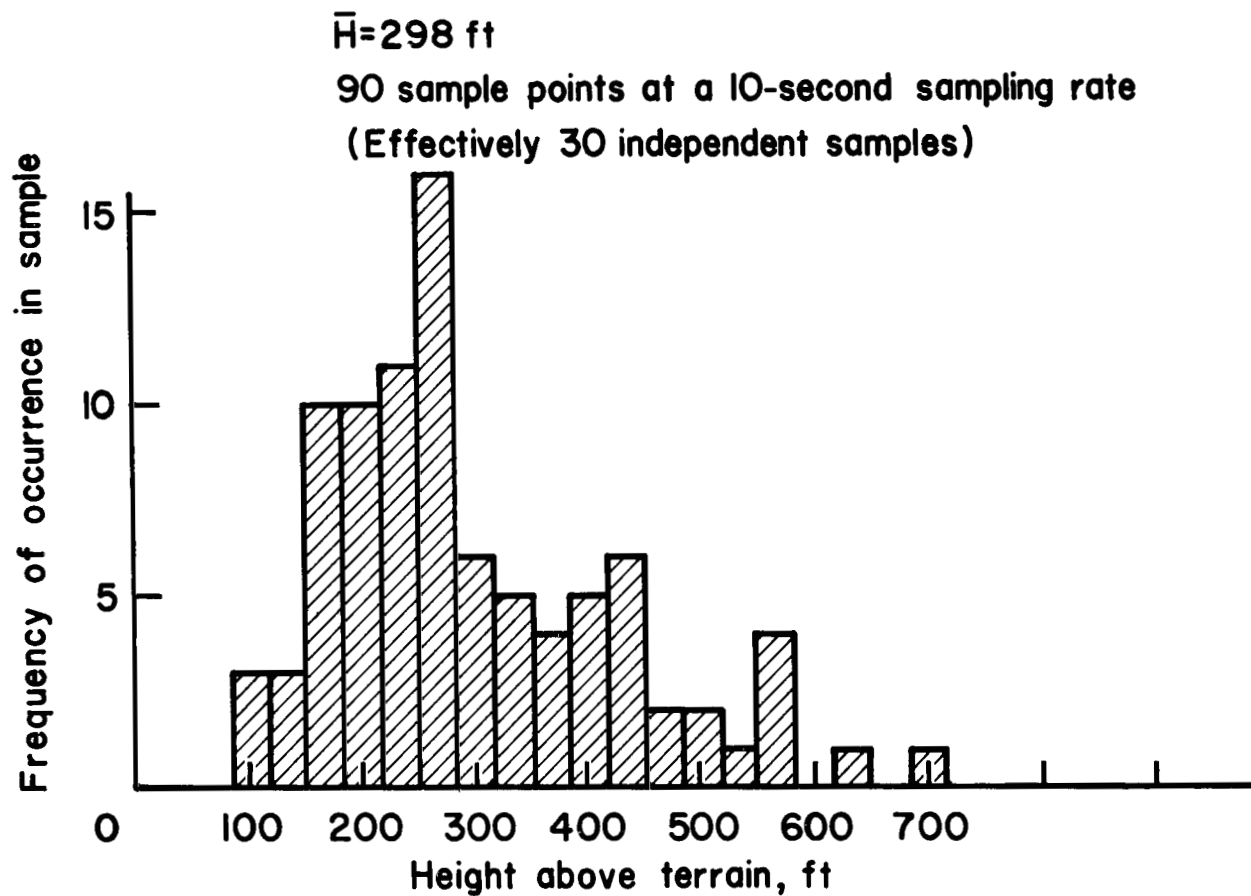


Figure 8.- Histogram of height above terrain; simulated terrain-following using display F.



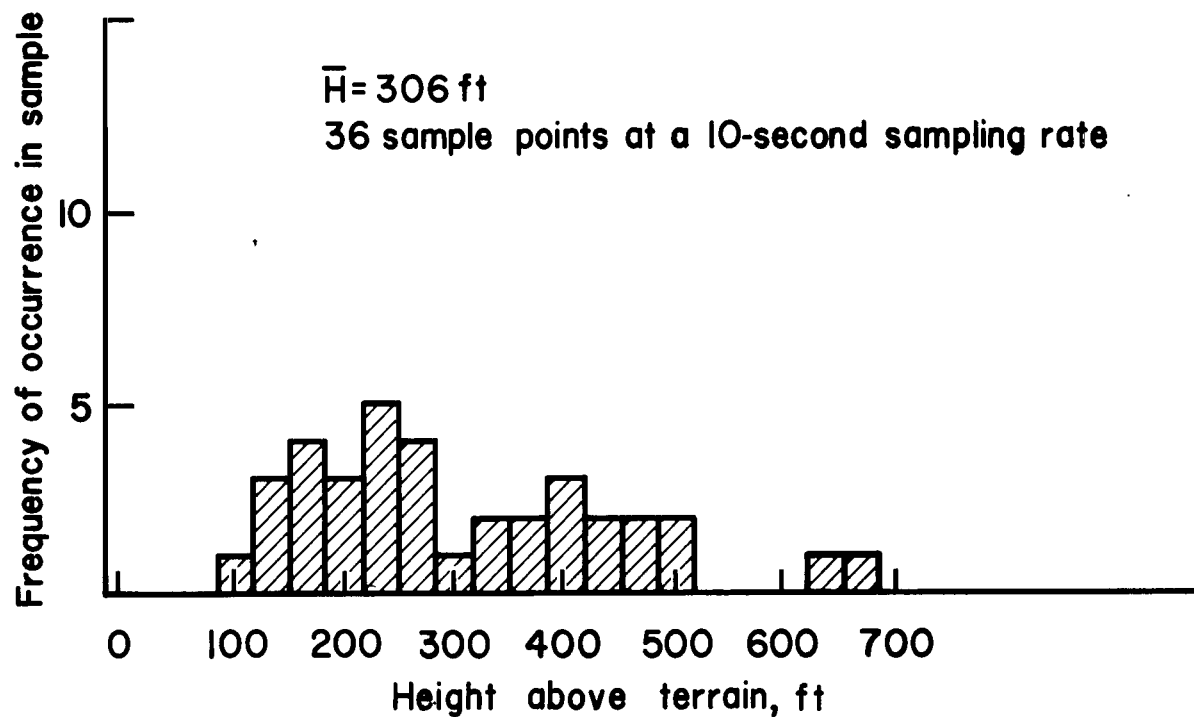
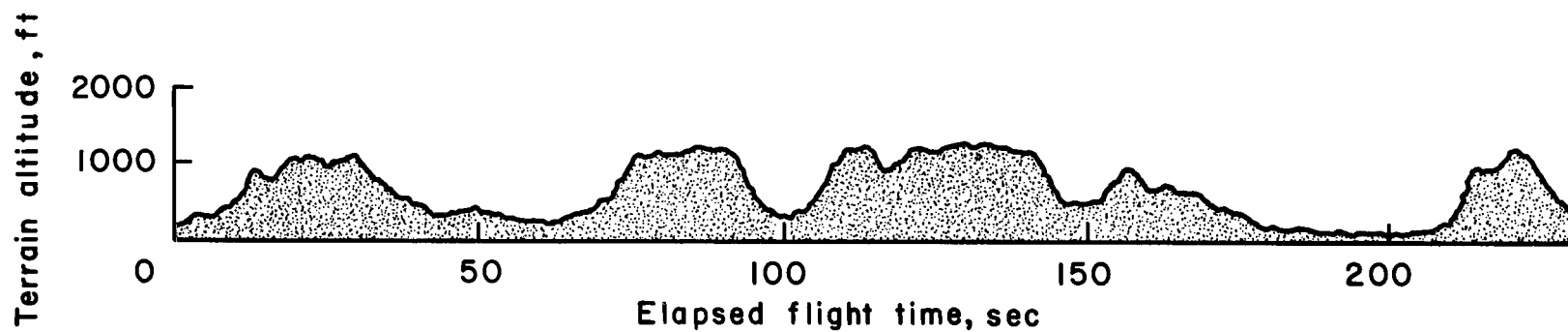
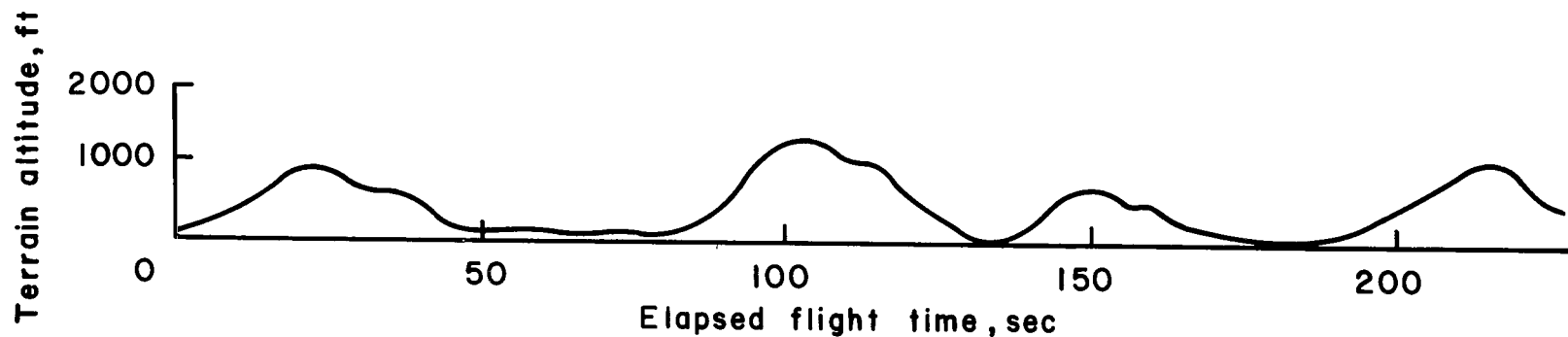


Figure 9.- Histogram of height above terrain; visual terrain-following over hilly African desert with maximum effort in a Hunter 6 at a Mach number of 0.7. (Data were extracted from ref. 3, fig. 3(c).)

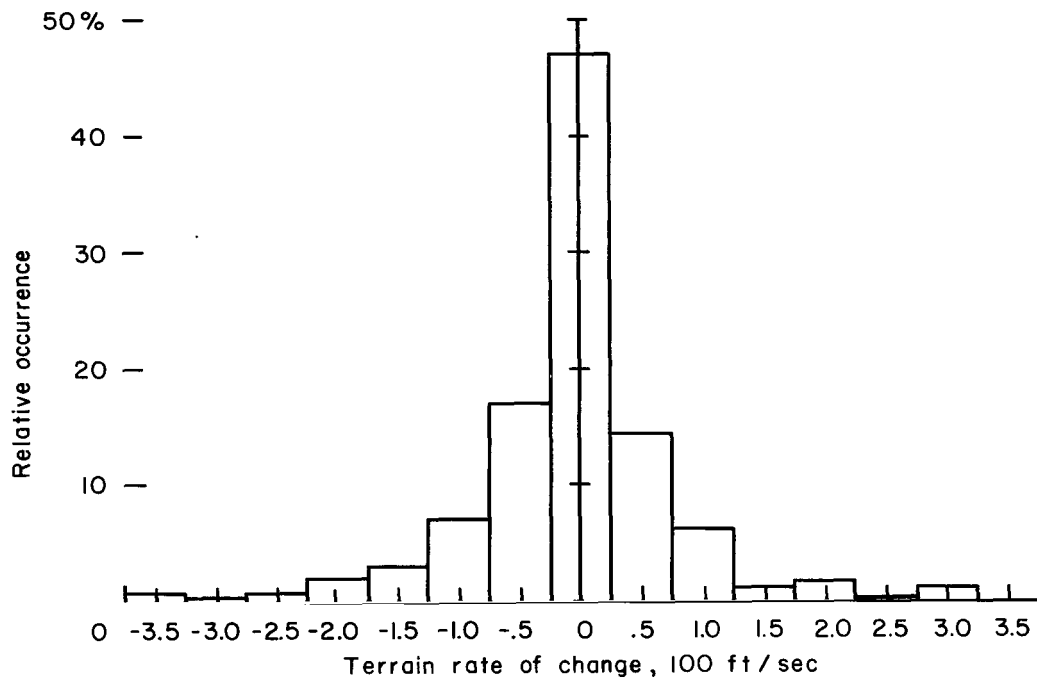


(a) Profile of hilly African desert as flown over at a Mach number of 0.7 (a portion of fig. 3(e) of ref. 3.)

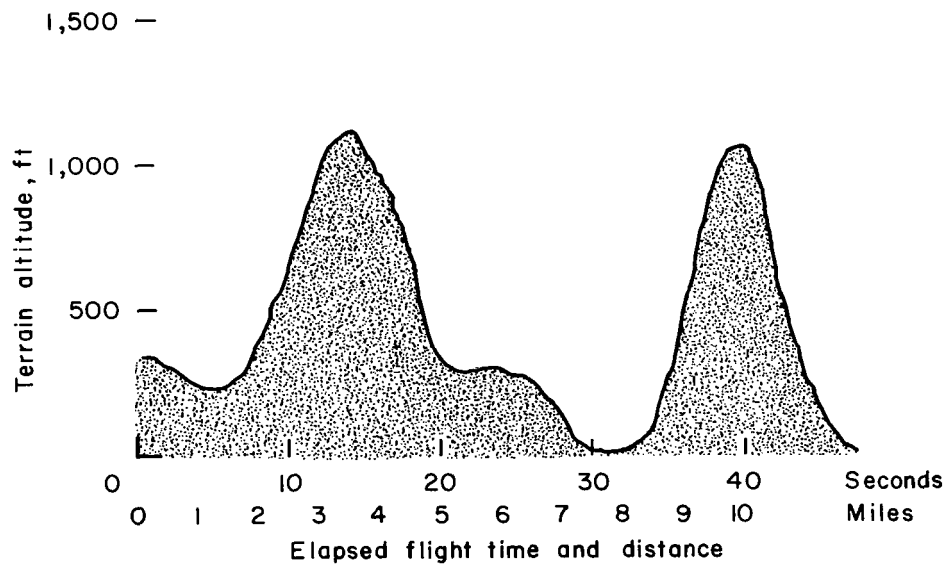


(b) Sample profile of the reduced-frequency simulated terrain of this study (Mach number 1.2).

Figure 10.- Comparison of terrain for two studies.



(a) Histogram of 200-data points at a 10-second sampling rate.



(b) Sample profile of the simulated terrain.

Figure 11.- High-frequency terrain generation.

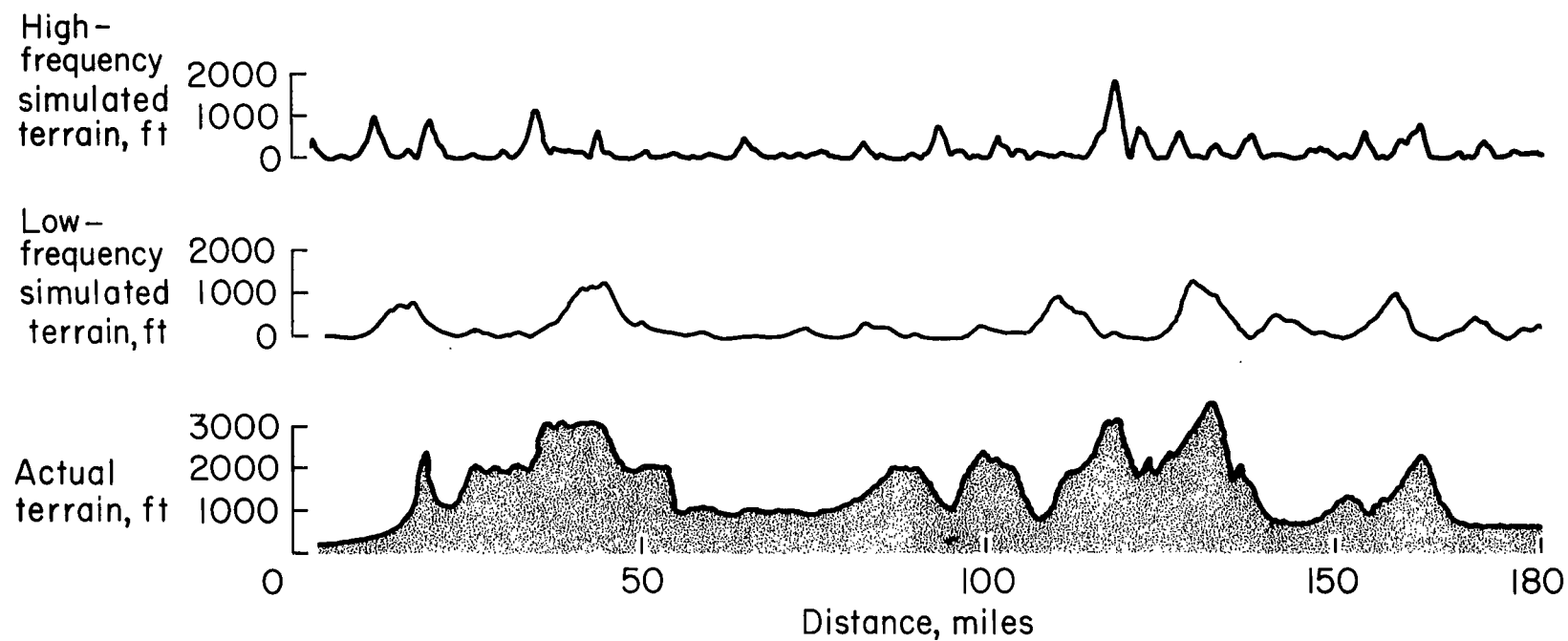


Figure 12.- Comparison of the high-frequency and low-frequency simulated terrain of this study with a sample of hilly California terrain (Oakland to Avenal via V-107).

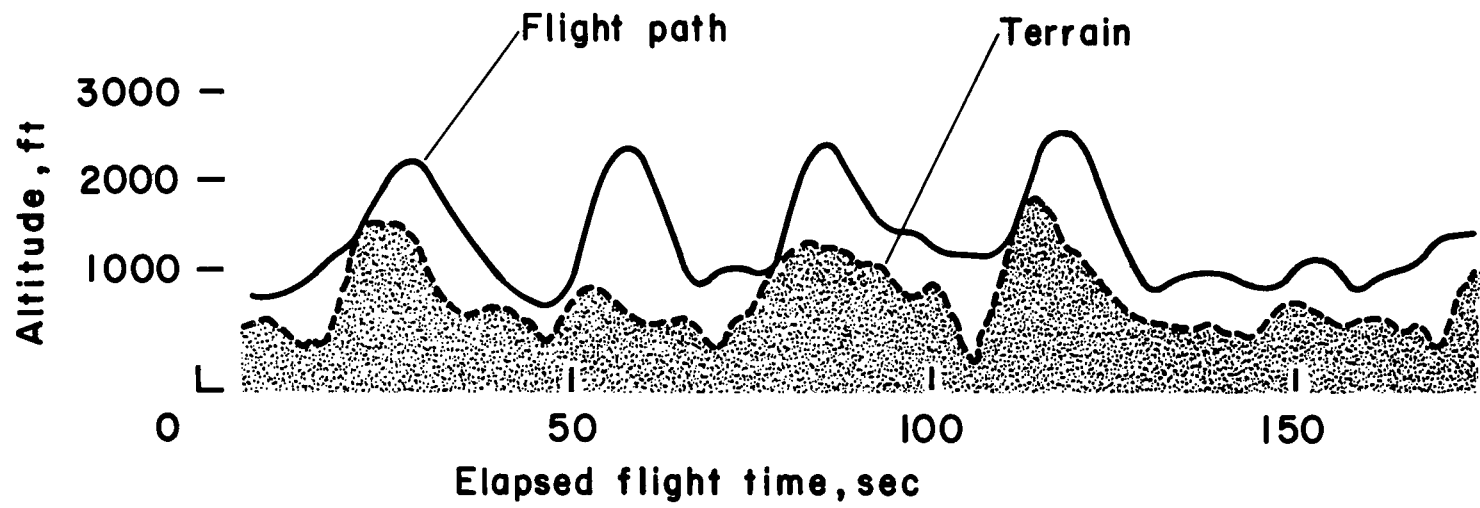


Figure 13.- Sample of performance in simulated terrain-following using display C.

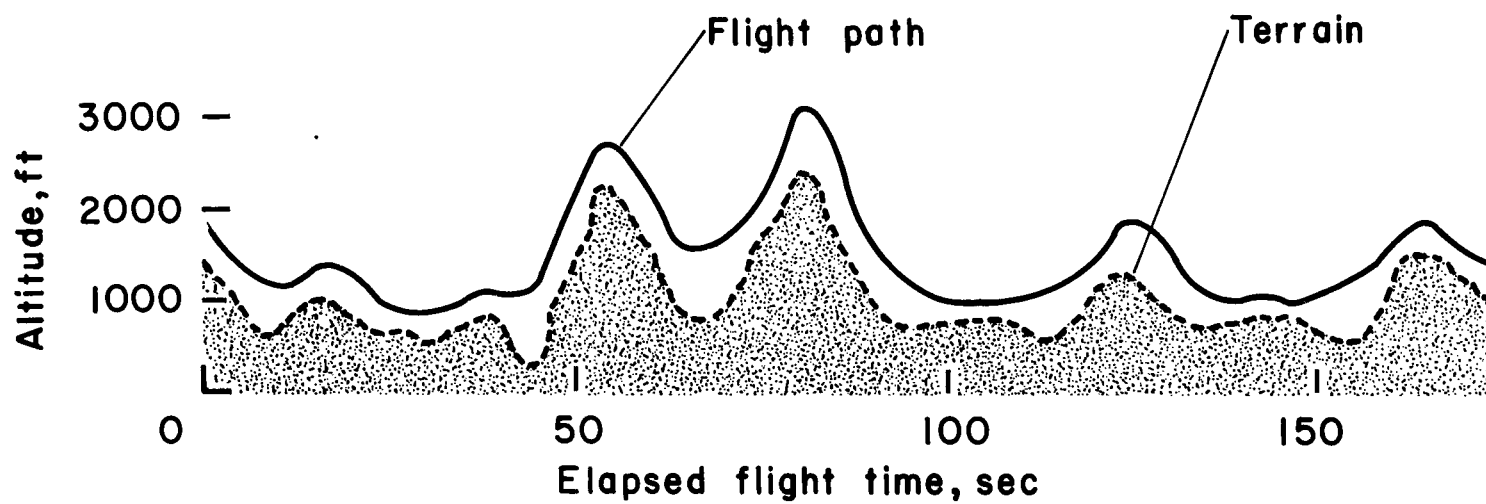


Figure 14.- Sample of performance in simulated terrain-following using display E.

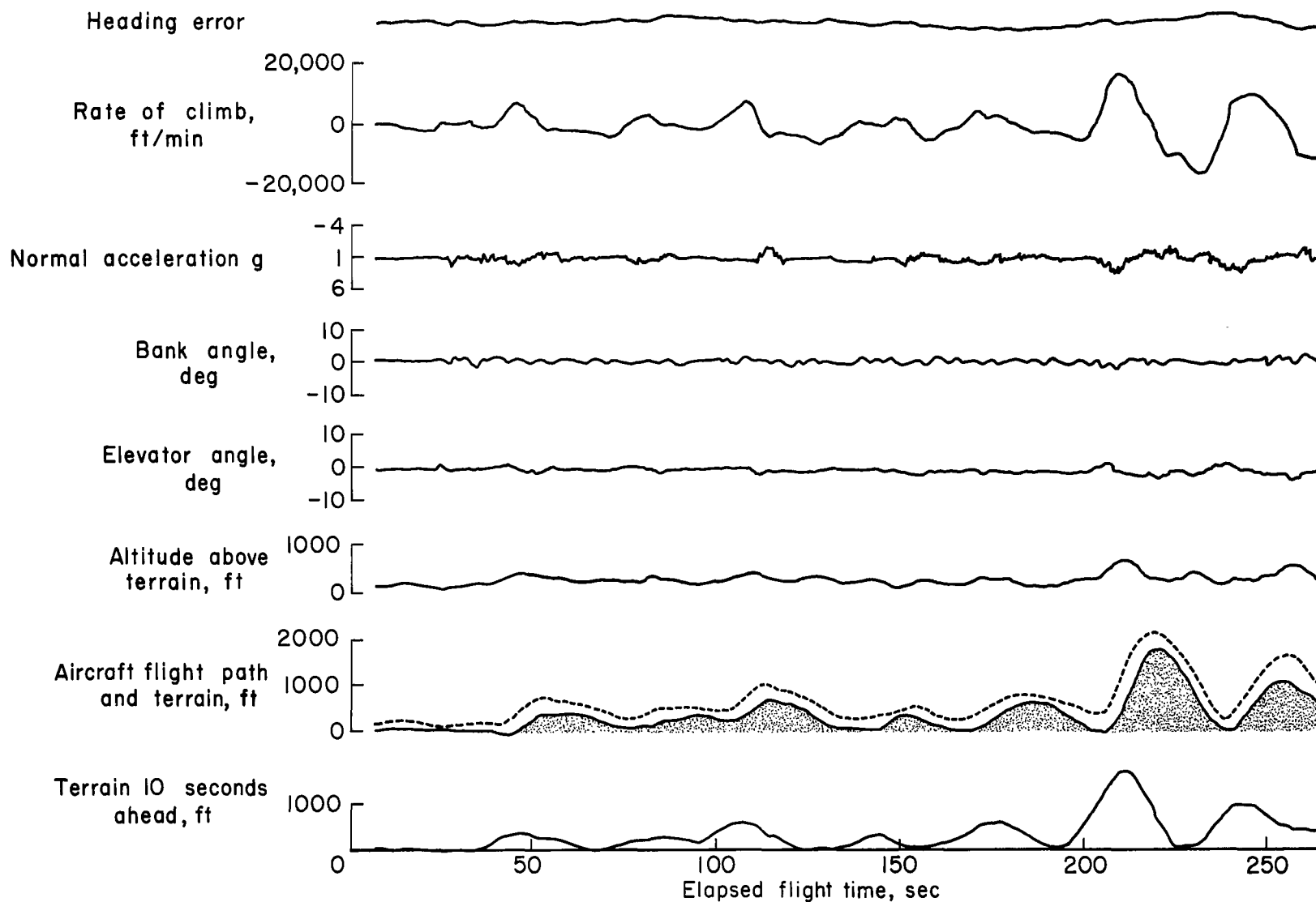


Figure 15.- Sample pen record of performance in simulated terrain-following using display F and reduced-frequency terrain.

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